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Weibull Analysis of Charpy Impact Test in Short Date Palm Fiber Reinforced Epoxy Composite

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Abstract

This study is a contribution to the valorization of natural fiber, which improve sustainability by substituting non-renewable raw materials by natural renewable resources. In this work, the fabrication and investigation of composite date palm fiber reinforced epoxy (DPFE) and compare it with an unreinforced epoxy resin (ER). One volume fraction, 10% by volume, of short date palm fiber (2–3 cm in length) was considered. A dynamic impact characterization of DPFE and ER are obtained by using the Charpy impact test. The Williams method based on the principle of linear elastic fracture mechanics was used to deduce the impact toughness of composite. The experimental results were statistically analyzed by using the two and three parameter Weibull distribution in order to evaluate the survival/reliability probability of the studied composite. It is found that the DPFE composite has better properties than the ER material in Charpy impact test.

Keywords

Charpy impact strength, epoxy resin, date palm fiber, Weibull distribution, survival/reliability probability

1 Introduction

In the context of the global energy crisis, environmental problems and depletion of resources, composites based on natural fibers have received considerable attention for different applications of life, such as the aerospace, marine, automotive and construction industries. These naturally occurring fibers have several advantages, including compatibility with most thermoplastic and thermoset matrices, renewable, lightweight and less abrasive [1–2]. Several natural fibers have been proposed as reinforcement or substitute for inorganic fibers, among which the date palm fiber, which is characterized by a high biodegradability, a low cost and an acceptable specific resistance [3].

Many research works have been published in recent years concerning the characterization of composite materials reinforced with natural fibers with the aim of replacing or combining these fibers with organic or inorganic ones. Indeed, Swain et al [4] have studied the effect of hybridization of inorganic glass fibers and organic date palm fibers on the thermal and mechanical behavior of epoxy resin-based composites. The results obtained show that the mechanical properties in bending and static tension undergo a significant improvement by adding different percentages of date palm fibers. However, recently reported research work has shown that natural fibers exhibit poor interfacial adhesion with synthetic matrices, which is mainly due to the hydrophilic nature of the fibers and the large percentage of cellulose [5]. In addition, Shanmugam and Thiruchitrambalam [6] studied the mechanical properties of hybrid polyester resin composites reinforced with date palm fibers and jute fibers and confirmed that alkali treatment of the fibers improved the static and dynamic properties of the composites, and the hybridization of the fibers and the alkali treatment reduced the possibility of delamination of the fiber-matrix interface, resulting in fewer fiber pullouts.

The various structural components based on composite materials can be subjected to static and/or dynamic loads that subsequently cause damage and cracking, sometimes catastrophic. It is very important to predict the mechanical response and behavior of these components at the time of service by implementing static and dynamic characterization tests. Among the dynamic characterization tests, the

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Charpy impact test is used to measure the impact resilience and toughness of uncracked materials (without notches) and pre-cracked materials (with notches). The results of the Charpy impact test on pre-cracked parts can be interpreted using the principles of linear elastic fracture mechanics in order to deduce the rate of energy restitution (impact toughness) based on the Williams method known as the complacency method [7–9]. However, other aspects of the interpretation of the impact response of composite materials have been published by a large number of authors in recent years. Indeed, Fitri and Mahzan [10] evaluated the effect of fiber content, fiber size and alkali treatment on the impact resistance of oil palm fiber composite material. They found that the oil palm fiber content significantly affects the impact strength of the polymer matrix composite. Salvati Pour et al. [11] conducted a comparative study between the experimental and theoretical results of Charpy impact test by establishing an analytical prediction model. Miao et al. [12] proposed a new modeling method called the velocity-controlled rigid body dynamic method to establish the geometric model of reinforced composites subjected to dynamic impact loading.

However, the anisotropic microstructure of composite materials has a negative effect on strength and causes very complex damage and failure mechanisms under impact loading. As a result, the results of characterization tests, whether static or dynamic, show important dispersions, especially for impact tests on notched specimens. Therefore, there is a strong need to use statistical methods to interpret the experimental data of the Charpy impact test based on failure probabilities and survival probabilities, to achieve a better design of composite materials, and to ensure the stability of the loaded elements [13]. Gong et al. [14] performed Vickers indentation tests on a commercial soda-lime glass to determine fracture toughness. The variability of the measured impact strength was statistically modeled by using Weibull probabilities in order to increase the reliability of the widely scattered results. Takashima et al. [15] proposed a method based on the weakest link theory and the two-parameter Weibull probability theory to evaluate the dispersion of the absorbed energy of the Charpy impact test of a brittle fracture model.

The main objective of this work is to predict the Charpy impact behavior and dynamic resilience of composite material based on epoxy resin and date palm fibers by using two and three parameter probabilistic Weibull analysis.

2 Methods and experimentation

2.1 Materials

The materials used in this study were:

Epoxy resin is a liquid thermosetting polymer of the medapoxy STR type, consisting of two components. It is cross-linked at room temperature by adding a hardener. It passes successively from the initial viscous liquid state to the gel state, then to the infusible solid state. The density is about 1.1 with a viscosity of 11000 MPa.S for a temperature of 25°.

A short date palm fiber reinforcement (2–3 cm in length) having a diameter of about 600 µm, an average density of 1.1 g/cm^3, a modulus of elasticity of 5.1 GPa and an elongation at break of about 21.4% [16].

2.2 Composite preparation

Rectangular DPFE composite plates were prepared by the contact molding method, which consists in depositing on the shape of the plate to be, molded a succession of multidirectional date palm fibers with epoxy resin up to a percentage of fibers of about 10% by weigh (Fig. 1). The even distribution of fibers inside the epoxy resin is ensured by the use of a soft brush and roller. In addition, the use of air gun to gently is strongly necessary to reduce or eliminate air bubbles inside the composite material.

2.3 Charpy impact test

The specimens used in the impact test are prismatic in shape, 80 mm long, 10 mm wide and 4 mm thick on average, with a single edge notch according to EN-ISO-179-1 [17]. The distance between supports of the order of 64 mm imposed by the devices of the impact apparatus corresponding respectively to a length of 80 mm was tested.

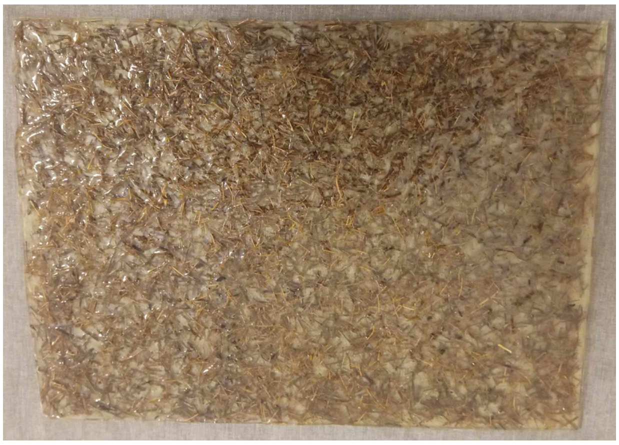


Fig. 1 Date palm fiber and epoxy resin plate

The specimens were cut on plates and then notched in the middle at different depths as shown in Fig. 2. A pre-notch is first made with a special diamond saw and then the notching is continued in a device using a rigid surgical blade in order to have a very sharp shape of the crack bottom controlled by a microscope. The notch lengths are all in the ratio 0.2 < a/D < 0.6. Where a is the notch length and D is the notch width of the specimen, respectively. A total of 121 specimens were fabricated and tested under Charpy impact load (57 samples for ER resin and 64 samples for DPFE composite material).

The tests were performed on a Charpy Zwick 5113 Pendulum impact testers in 3-point bending (Fig. 3). The release angle of the machine is 160° and the impact speed is 3.85 m/s. The pendulum used in the case of the study materials has an energy of 7.5 Joules. Fig. 3 shows the experimental device used as well as the data acquisition and processing device by a microcomputer equipped with an expert test software.

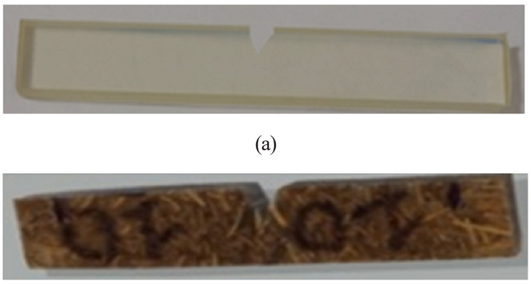
3 Theories of analysis

Weibull statistical analysis is used to exploit and interpret impact results as well as to assess the probability of survival/reliability of the tested materials. The two-parameter Weibull distribution is commonly used to better represent and exploit impact results. It is used to model extreme values such as fracture time and impact strength. In addition, it estimates the load dispersion and impact toughness, which can compare with reported data [18–21].

The probability density function (PDF) for a three parameter Weibull distribution is defined as follows [22–25]:

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x - x_{min}}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x-x_{min}}{\alpha}\right)^{\beta}}, \tag{1}$$

The PDF gives the cumulative probability distribution function (CPDF):



(a)

(b)

Fig. 2 Specimens used in Charpy impact test (a) Epoxy resin (ER), (b) Date palm fiber/epoxy (DPE)

$$P_f(x) = 1 - e^{-\left(\frac{x-x_{min}}{\alpha}\right)^{\beta}}, \tag{2}$$

$$P_s(x) = 1 - P_f(x) = e^{-\left(\frac{x-x_{min}}{\alpha}\right)^{\beta}}. \tag{3}$$

Where $P_f(x)$ is the probability of failure, $P_s(x)$ is the probability of survival or reliability index, α is a scaling parameter of the Weibull distribution representing the characteristic resilience in the context of this study, (α has the same dimension of x), β is the shape parameter or Weibull modulus that characterizes the degree of dispersion of the impact resistance, x is an independent variable that presents the resilience in the impact test analysis, xmin represents the minimum resilience value (a threshold).

The values of α and β are determined by rewriting Eq. (2) in the following form:

$$Ln\left(Ln\left(\frac{1}{1-P_f(x)}\right)\right) = \beta Ln(x - x_{min}) - \beta Ln(\alpha). \tag{4}$$

On Eq. (4) the relationship between $Ln(Ln(1/1 - P_f(x))$ et $Ln(x)$ is linear, the slope of the line shows the shape parameter: $m = \beta$ and the dispersion parameter α can be obtained by the second term in Eq. (4).

The two-parameter distribution is a special case of the Weibull distribution, which implicitly defines a zero-threshold value. Indeed, if $x_{\min}$ is zero, Eq. (2) of the CPDF takes the two-parameter Weibull according to the following equation:

$$P_f(x) = 1 - e^{-\left(\frac{x}{\alpha}\right)^{\beta}}. \tag{5}$$

Fig. 3 Zwick/Roell type Charpy impact machine used

The probability of rupture $P_f(x)$ is calculated from the following equation [25–27]:

$$P_f\left(x\right)=\frac{i-0.3}{n+0.4}, \tag{6}$$

where, i presents the number of damaged samples, and n presents the total number of samples.

The mean resilience before failure [V], standard deviation [SD] and coefficient of variation [COV] are calculated from the following equations [28, 29]:

$$\left[V\right]=\alpha\Gamma\left(1+\frac{1}{\beta}\right), \tag{7}$$

$$\left[SD\right]=\alpha\sqrt{\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)}, \tag{8}$$

$$\left[COV\right]=\frac{\left[SD\right]}{\left[V\right]}=\frac{\sqrt{\Gamma\left(1+\frac{2}{\beta}\right)-\Gamma^2\left(1+\frac{1}{\beta}\right)}}{\Gamma\left(1+\frac{1}{\beta}\right)}. \tag{9}$$

Γ is the gamma function.

The coefficient of variation of Eq. (9) is as a function of parameter β, according to [30] this coefficient can be calculated by using Eq. (10) for values of $\beta > 8$.

$$\left[COV\right]=\frac{1.2}{\beta} \tag{10}$$

4 Results and discussion

4.1 Charpy impact behavior

The experimental resilience R of notched specimens is calculated in accordance with EN-ISO-179-1 [17] using the following equation:

$$R=\frac{U}{B.\left(D-a\right)}. \tag{11}$$

The Charpy impact test on the DPFE composite allows to deduce the impact toughness G_{IC} which represents the resistance of materials to the propagation of cracks at the time of loading, by using the Willams theory according to the following equation [7]:

$$U=\left[G_{IC}BD\phi\right]+U_C, \tag{12}$$

where B and D represent the thickness and width of the specimens, respectively, ϕ represents the calibration factor, which is calculated by Eq. (2), it is a function of specimen dimensions and notch length, U_c is the kinetic energy.

$$\phi=\frac{1}{2}\left(\frac{a}{D}\right)+\frac{1}{36\pi}\left(\frac{L}{D}\right)\frac{1}{\left(\frac{a}{D}\right)}, \tag{13}$$

where a and L represent the notch length and the distance between supports, respectively.

The Williams method known as the complacency method is based on the principles of linear elastic fracture mechanics, it plots the absorbed impact energy (fracture energy) U as a function of the ruptured areas $BD\phi$ of all tested specimens, the slope of the linear regression line represents the impact toughness in KJ/m^2 (Fig. 4 and Fig. 5). B and D represent the thickness and width of the specimen, respectively.

The point of contact of the regression lines with the energy axis corresponds to a positive energy for this type of composites studied. This energy is part of the total energy measured and contributes significantly to the rupture corresponds to the kinetic energy UC of the material.

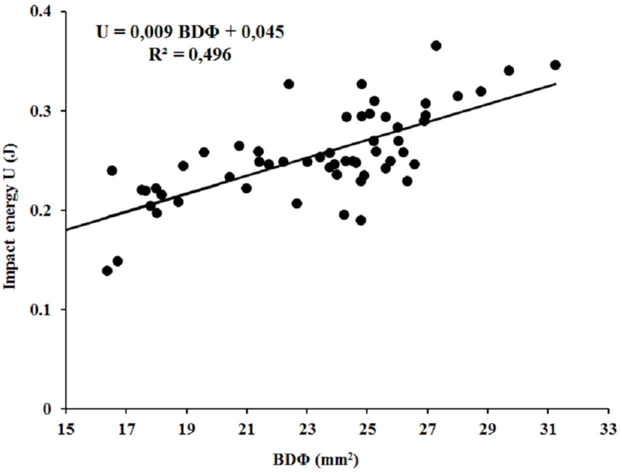


Fig. 4 Total fracture energy vs. fractured areas of ER epoxy resin

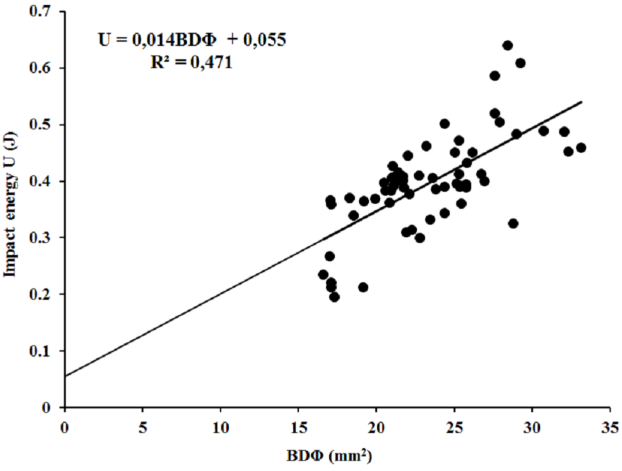


Fig. 5 Total fracture energy as a function of broken areas of DPE composite

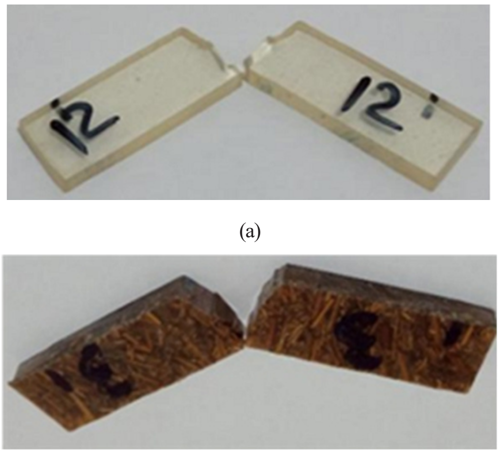
The experimentation proved to be complex due to the shape and geometry of the tested specimens as well as the precision of the machine with a high speed of the impact pendulum. However, many specimens were operated in Charpy impact with different notches in order to deduce the resilience in Charpy impact and the dynamic toughness of ER and DPFE. Table 1 shows the average values of the impact test results and the standard deviation of the two materials studied.

The Charpy impact energy results of the two materials tested show a significant variation that is a function of the nature of the reinforcement as well as the percentage of fibers in the material.

The graphical presentation of the impact energy as a function of the ruptured areas (Fig. 4 and Fig. 5) shows that the total fracture energy increases with increasing ruptured areas, which indicates that fracture is an energy-consuming phenomenon, thus increasing ruptured areas requires more fracture energy. In addition, the Charpy impact strength (R = 8.81 KJ/m^2, Table 1) and dynamic toughness (GI_C = 14.60 KJ/m^2, Fig. 5) values of DPFE composite which contains 10% of the fibers are more important than the values of ER (R = 5.8 KJ/m^2, GI_C = 9.0 KJ/m^2). This difference in strength is mainly due to the impregnation of the date palm fibers with the epoxy resin, which creates barriers in front of the cracks and minimizes the damaged section. In addition, the epoxy matrix binds the fiber assembly acts as a means of transmitting external loads to the fibers, which increases the Charpy impact resilience of the material with the increase in reinforced sections. On the other hand, the date palm fibers behave as a barrier to the force applied by the crack pinning mechanism [31]. So, the fracture in the DPFE composite follows a fiber guided direction and the crack propagates along the fiber direction [32]. Unlike the unreinforced material, which contains 0% fibers, the cracks propagate in an arbitrary direction. However, all the specimens tested in Charpy impact (ER, DPFE) are completely ruptured reflecting the brittle character of these two types of materials (Fig. 6). It is strongly necessary to mention that the brittle fracture of these materials is characterized by the total rupture of all the specimens tested and the absence of a damaged zone. Contrary to the ductile fracture which represents a damaged section before failure. A high Charpy impact resilience indicates a high toughness, and consequently, a high resistance to crack propagation due to stress concentrations around the critical section.

Table 1 Fracture energy, Charpy impact resilience and ruptured areas of materials: ER, DPE

Materials	U (J)	R (KJ/m^2)	ϕ	U_c (J)	$BD\phi$ (mm^2)
ER	0.25 (0.04)	5.8 (0.69)	0.35 (0.04)	0.045	23.34 (3.52)
DPE	0.39 (0.08)	8.81 (1.27)	0.33 (0.034)	0.055	23.35 (3.99)



(a)

(b)

Fig. 6 Impact damaged specimens

The linear regression line of the curves in Fig. 4 and Fig. 5 gave a positive intersection with the U ordinate line, which is due to the effects of the kinetic energy transmitted to the specimens during the impact test. For the ER presents a value of kinetic energy of about 0.045 Joule, which is less important than the value of the DPFE composite which about 0.055 Joule. It is highly possible that this increase in kinetic energy for the DPFE composite is mainly due to the presence of fibers within the material, which leads to an increase in the weight of the tested specimens. In addition, the presence of date palm fibers can improve the mechanical strength of the epoxy matrix, transferring mechanical forces to the fibers while protecting them from external aggression and giving cohesion to the material. It is important to note that any kinetic energy transferred to the specimens first enters as strain energy, as momentum is transmitted to the outer ends (supports) by shear waves passing outward along the beam [9].

The calculated impact toughness results of the Charpy impact test on all the tested specimens show correlation coefficient values of 0.70 and 0.68 for ER and DPFE composite respectively, reflecting the dispersion of the results of the impact energy of the cracked specimens around the linear regression line. This dispersion is essentially due to the presence of defects during the manufacture of the specimens, in particular for the DPFE composite which probably presents a non-uniform distribution of the rate of date palm fiber in the epoxy matrix. This non-uniform distribution of the fibers can causes often tortuous paths of rupture which do not necessarily follow the direction of the initial notch and which are different from one specimen to another.

4.2 Weibull statistical analysis

The previous section discussed the observations made based on geometric mean values by using the principles of linear elastic fracture mechanics to evaluate the impact toughness of the two materials studied. Despite the large number of notched specimens used in the impact test, it should be noted that these results show a significant dispersion, which requires a probabilistic analysis based on the two and three parameter Weibull statistical distribution. This analysis is used to predict the impact toughness of the materials used and to compare with the experimental data. The Weibull parameters were calculated by fitting the cumulative probability distribution function of the data in a least squares sense. Fig. 7 and Fig. 8 show the two-parameter and three-parameter Weibull curve fitting of the Charpy impact test results of the ER and DPFE composite, respectively. By plotting the linear regression lines of the experimental data of the two materials studied, the slope that represents the value of β and the dispersion parameter α can be deduced (Table 2).

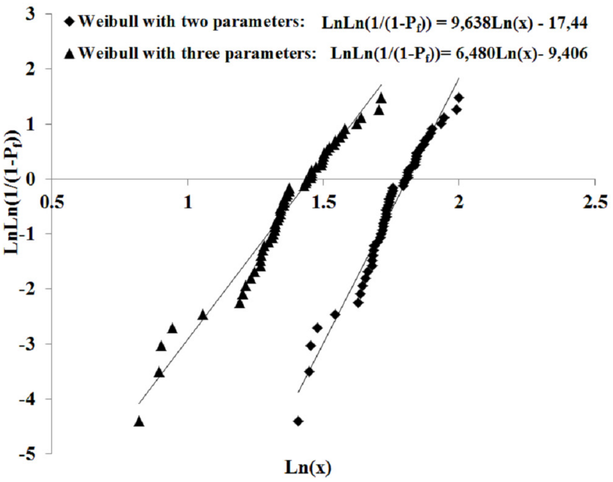


Fig. 7 Weibull probability plot of epoxy resin ER materials

It is well noticed on Fig. 7 and 8 as well as Table 2 that the values of the confidence index R^2 are higher than 0.96 reflecting the good correlation of the experimental data as well as the reasonable fit of the 2 and 3 parameter Weibull distribution. In addition, all predictions generally follow the trends of the experimental data. In fact, the scale parameter α obtained by the three-parameter Weibull analysis of the ER and DPFE composite studied presents smaller values to the values obtained by the two-parameter Weibull analysis, which is mainly due to the presence of the location parameter $x_{\min}$, which represents the minimum value of the resilience.

The fracture energy as well as the impact toughness follow a distribution characterized by the Weibull modulus β and the scaling parameter α. These parameters are a function of the interaction between the pre-existing defect distribution and the stress displacement fields due to the shock loading. However, the large shock pendulum velocity, which is about 3.85 m/s, leads to a variety of phenomena that occur at the time of loading and cracking of the notched specimens. The shape parameter β obtained by the two and three parameter Weibull analysis shows less significant values of the DPFE composite compared to the ER.

It is highly possible that this difference is mainly due to the impregnation of date palm fibers with epoxy resin,

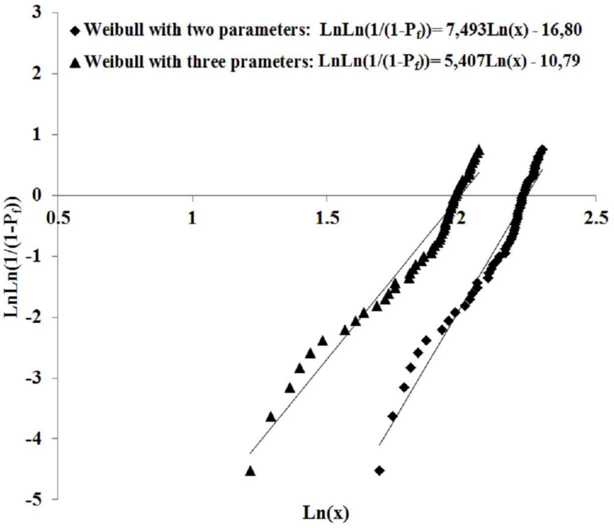


Fig. 8 Weibull probability plot of DPE materials

Table 2 Weibull parameter for the Charpy impact test

Material	Weibull analysis	α	$x_{\min}$	β	R^2	[V]	[ET]	[COV]
ER	2 p	6.107	-	9.638	0.966	5.801	0.723	0.124
	3 p	4.269	1.808	6.481	0.964	3.974	0.728	0.183
DPE	2 p	9.425	-	7.528	0.956	8.850	1.389	0.157
	3 p	7.294	2.076	5.578	0.962	6.740	1.397	0.207

which certainly present a non-uniform distribution of these fibers within the composite material, with the creation of voids and micro pores of different dimensions and shapes. The presence of these fibers leads, at the same time, to an increase of the GIC toughness by the absorption of the impact energy, and a decrease of the homogeneity of the DPFE composite compared to the ER.

Three- and two-parameter probabilistic Weibull analysis is used not only to discuss the effect of fiber rate on impact strength, but also to predict and quantify its threshold values. Thus, probability and reliability take on greater importance for the design of these materials. Indeed, the values of the average resilience calculated by the two-parameter Weibull analysis show very close values to the values calculated by Eq. (11), reflecting the reliability of this analysis. In contrast, the three-parameter Weibull analysis, which considers that the minimum resilience of the tested materials is not equal to 0 ($x_{\min} \neq 0$), presents less significant values.

However, it is strongly necessary to point out that the sum of the values of the average resilience and the minimum resilience deduced by the three-parameter Weibull analysis is equal to the average resilience calculated by the two-parameter Weibull ($x_{\min} = 0$), and therefore, equal to the value obtained by Eq. (11). The three-parameter Weibull analysis offers more security than the two-parameter Weibull analysis by imposing a threshold impact value above which the material is considered damaged, and therefore, the average impact can be written: [V] = 3.97 ± 1.808 KJ/m^2 and [V] = 6.74 ± 2.076 KJ/m^2 for the ER and the DPFE composite, respectively.

The coefficient of variation [VOC] of the ER is lower than that of DPFE composite, reflecting the low dispersion of the results as well as the uniform distribution of voids and micro pores in the unreinforced material. Indeed, the impregnation of date palm fibers with epoxy resin by the contact molding method results in manufacturing defects and non-uniform distribution of fibers. This tendency of dispersion of impact results is extremely important for designers and engineers and deserves much attention before using this type of materials [33].

The reliability of the impact-loaded specimens can be evaluated considering the resilience for different reliability level. To plot the survival probability of two and three Weibull parameters as a function of the resilience of ER and DPFE composite (Fig. 9 and Fig. 10), Eq. (4) is used, which has a linear function:

$$Ln(x),\ Ln\left(Ln\left(\frac{1}{1-P_f(x)}\right)\right), \tag{14}$$

where: $-\beta Ln(\alpha) = C$, Eq. (14) can be derived:

$$\alpha = e^{\left(-\frac{C}{\beta}\right)}. \tag{15}$$

The probability of survival curves plotted in Fig. 9 and Fig. 10 are of considerable value to the designer, allowing the resilience of the ER, and DPFE composite tested to be determined at any percentage survival. The 90% probability of survival can be determined from these curves by drawing a horizontal line that intersects with the two and three parameter Weibull distribution curves. The values at the intersecting points are the resiliencies for a 90%

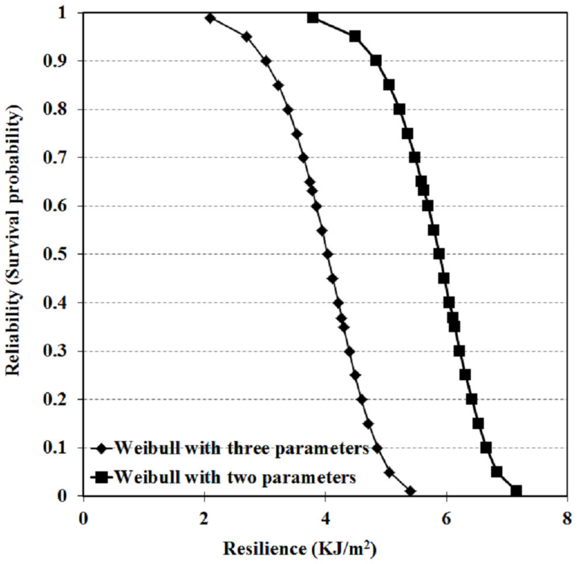


Fig. 9 Survival probability of ER epoxy resin material

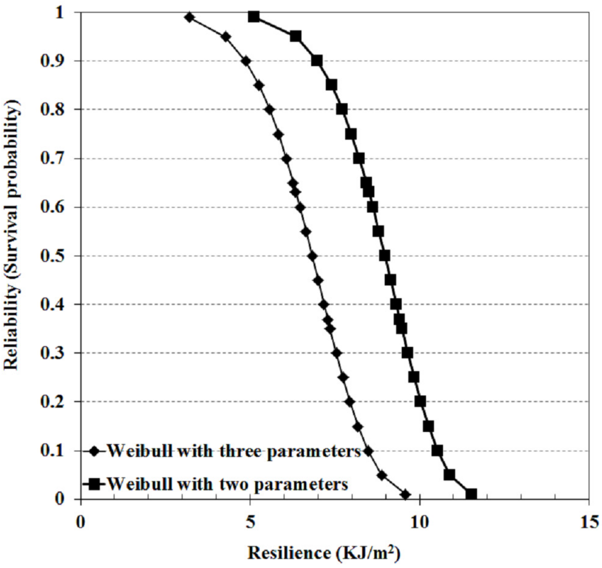


Fig. 10 Survival probability of the DPE composite material

survival probability at two and three Weibull parameters. For example, for ER, the intersection of the horizontal line for a 10% survival probability yields an impact resilience value of 6.66 KJ/m^2 and 4.85 KJ/m^2 from the two-parameter and three-parameter Weibull distribution, respectively. These resilience values and for the same percentage of survival probability (10%), became to 10.52 KJ/m^2 and 8.47 KJ/m^2 for the DPFE composite.

5 Conclusions

The DPFE composite was characterized under dynamic impact in order to deduce the resilience and toughness of this material. The results were statistically analyzed by using the two and three parameter Weibull distribution. From those test and statistical analysis results, the following conclusions may be drawn:

The DPFE composite has higher Charpy impact resilience and toughness compared to the unreinforced ER.

The Charpy impact toughness obtained by the Williams theory based on the principles of linear elastic fracture mechanics confirm the brittleness of the composites studied.

The probabilistic analysis of the shock data using the two- and three-parameter Weibull distribution shows resilience results very close to the experimental calculation reflecting the reliability of the analysis.

The two- and three-parameter Weibull cumulative density function predicts the survival probability/reliability of ER and DPFE composite.

The three-parameter Weibull distribution is highly recommended in this type of characterization since it offers more security and reliability.

The survival probability graphs obtained by the Weibull parameter analysis are considerably important to designers and engineers to identify the first time of failure, because the safety limits of elements on practical applications depend on the confidence index.

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